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First rotation biomass production and nutrient cycling within short-rotation coppice willow plantations in Saskatchewan, Canada

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First rotation biomass production and nutrient cycling within short-rotation coppice willow plantations in Saskatchewan, Canada.

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Key Words: canopy exchange, dry deposition, fine root turnover, leaf litter decomposition, leaching, nutrient budget, *Salix*, soil mineral weathering, zirconium

Abbreviations: **BD**, bulk deposition**; CE**, Canopy Exchange; **DD**, Dry Deposition; **NTF**, net throughfall**; SOM**, soil organic matter; **SRC**, short-rotation coppice; **TF**, throughfall

Abstract

Although numerous studies have quantified different social, economic, energetic, and environmental benefits associated with short-rotation coppice (SRC) willow plantations, comprehensive assessments of nutrient cycling are rare. The objective of this study was to examine the biomass production and attendant biogeochemical cycling of nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), and magnesium (Mg) during the initial four-year rotation of six willow varieties grown at four locations along a 500 km north-south pedoclimatic gradient within Saskatchewan, Canada. Nutrient budgets consisted of quantifying various nutrient inputs (e.g., atmospheric deposition and soil mineral weathering), outputs (e.g., fine and coarse root biomass, leaf biomass, harvested biomass, leaching, and denitrification), and transfers (e.g., soil organic matter mineralization, canopy exchange, leaf litter decomposition, and fine root turnover) associated with the plant available soil nutrient pool. Total above- and below-ground production during the rotation was approximately 40 Mg ha^{-1}, with calculated soil nutrient budget deficits (i.e., nutrient outputs > inputs + transfers) of 17, 39, 112, 271, and 74 kg ha^{-1} for N, P, K, Ca, and Mg, respectively, averaged across the varieties and sites, but a soil S surplus of 60 kg ha^{-1}. While soil nutrient budget deficits varied among sites, there were no significant differences (P >0.05) among willow varieties. Despite the relatively low nutrient-demanding nature of willow and negligible leaching or denitrification losses, nutrient export in harvested biomass over multiple rotations will require soil nutrient amendments to maintain SRC willow productivity, particularly N and P, albeit a fraction of the amount required for annual agronomic crops.

Introduction

Sensitivity analyses are a common component of a life cycle analysis and often identify biomass production as a primary controller of both economic viability [18,33,71], along with net energetic [48,70,103] and net greenhouse gas emission sustainability [17,103,110] of short-rotation coppice (SRC) willow plantations. Under conditions of adequate soil moisture, willow productivity will be primarily controlled by soil nutrient availability. A fundamental question concerning sustainable SRC willow yields, therefore, is whether long-term soil productivity is maintained within a multi-rotation production system, given the rapid growth rate and nutrient exports offsite when harvesting the willow biomass after repeated short rotations. Fertilization traditionally has been used as a management tool to support the establishment and growth of willow plantations, however, its efficacy has been inconsistent [42], which is disconcerting given that it constitutes a large portion of SRC willow production costs [45,71]. Furthermore, after examining all published SRC willow life cycle analyses, Djomo et al. [26] reported that minimizing fertilizer additions was key to optimizing the net energy ratio (i.e., energy output:fossil energy input) and reducing net greenhouse gas emissions of willow biomass energy production. Additionally, superfluous fertilizer application has been linked to decreased plantation productivity, either directly due to fertilizer toxicity [77] or indirectly by stimulating weed species growth [10,121] or inducing soil nutrient imbalances [60,80]. Non-point source pollution associated with excessive and non-timely fertilizer application has also been reported [8,25,102].

A clear understanding of soil nutrient dynamics, particularly the soil nutrient budgets of essential plant nutrients during the establishment phase, is required to accurately forecast the sustainability of the SRC willow production system and the necessity of nutritional amendments. Influential factors include the inherent soil fertility at a given site [76,89], genotypic variability in nutrient requirements, uptake capacity, and/or utilization efficiency [2,121], and genotype × environment interactions [11,49]. In order to account for these effects when developing reliable nutrient budgets for SRC willow production in Saskatchewan, an experiment consisting of several commercial willow varieties was replicated at different sites across a 500 km north-south gradient, covering the range of soils and climate in the province. The objective of this study was to quantify the biogeochemical cycling of nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), and magnesium (Mg), within SRC willow plantations during the initial four-year rotation, to provide insight into the long-term sustainability and productivity of these woody biomass energy production systems grown in Saskatchewan over multiple rotations.

A prerequisite for providing a reasonable estimate of long-term sustainability across a variety of soil types is an accurate accounting of above- and below-ground nutrient pools, including: vectors of nutrient flux into (e.g., soil mineral weathering and atmospheric deposition), out of (e.g., fine and coarse root biomass, leaf biomass, harvested biomass, leaching, and denitrification), and transfers between (e.g., soil organic matter mineralization (SOM), canopy exchange (CE), leaf litter decomposition, and fine root turnover) the plant available nutrient pool. Although some excellent nutrient budget work has been done within SRC willow plantations [5,31,53], to our knowledge, this is the first study to carry out a comprehensive examination of all nutrient cycling vectors (i.e., input, output, and transfers), within different sites across a large pedoclimatic gradient, involving both fertile and marginal agricultural soil, growing the same willow varieties established concurrently. The study also examines S, an element sometimes deficient for annual grain crops in western Canada, but which has received little attention in SRC willow production systems. We hypothesized that the magnitude of nutrient cycling, along with the degree of depletion or accumulation in the various soil and plant pools, would vary according to specific nutrient, willow variety, and from site to site as related to the soil and environmental conditions and stand productivity. A tremendous opportunity exists to develop SRC willow as a bioenergy feedstock in Saskatchewan, especially if it can be sustainably grown on millions of hectares of marginal land that is deemed unsuitable for annual crop production.

Materials and Methods

Study sites, experimental design, willow varieties, and site maintenance

The data for this study were collected from four SRC willow variety trial plantations located along a 500 km north-south pedoclimatic gradient within Saskatchewan, Canada, from the south-east corner of the province to the southern boundary of the boreal forest in the central area of the province, which were selected to represent the diverse soil types and climatic conditions existing in the province (Tables 1 and 2). At each of the four sites, a single pedon was excavated and a full soil taxonomic assignment given (according to the Canadian System of Soil Classification) to classify the soils. The following replicated variety trial information was originally reported in Hangs et al. [43]. In the spring of 2007, six willow varieties, developed by the SUNY-ESF breeding program, were planted at each location in a randomized complete block design (n=4) adapted from the protocols of Abrahamson et al. [1]. The six willow varieties used were: Allegany *(Salix purpurea)*, Canastota *(Salix sachalinensis* × *miyabeana)*, Fish Creek *(Salix purpurea)*, Sherburne *(Salix sachalinensis* × *miyabeana)*, SX61 (*Salix sachalinensis*), and SX64 (*Salix miyabeana*). Each varietal plot (6.3 × 7.8 m) consisted of 78 plants (three double-rows of 13 plants row^{-1}), with spacings of 1.5 m between the double-rows, 60 cm

between rows within the double-row, and 60 cm between plants within the double-row; resulting in a planting density of approximately 15,873 plants ha^{-1}. In the spring of 2008, the willow plants were coppiced and grown for an additional three years before harvesting. In order to prevent edge effects, the central 18 plants constituted the measurement plot and were used for sample collection and biomass measurements. Pre- and post-planting site preparation to control non-crop vegetation included both mechanical (deep tillage, light cultivation, tandem disc, mowing, and hand weeding) and chemical (Goal™ 2XL, 2 L ha^{-1}; Roundup WeatherMax®, 2 L ha^{-1}; Simazine 480, 4.7 L ha^{-1}; Pardner®, 0.5 L ha^{-1}) treatments.

Measuring baseline plant available soil nutrient pools

The following soil analyses were originally reported in Hangs et al. [44]. After planting the willow varieties at each site, three 60 cm soil cores (2 cm diameter) were collected within each varietal plot using a JMC backsaver probe (Model PN001; Clements Assoc. Inc, Newton, IA, USA), separated into 10 cm depth increments, and composited. A 60 cm depth is believed to represent the effective rooting depth (i.e., contain the vast majority of roots) for most willow varieties [75,102]. Additionally, bulk density cores (100 cm^3) were collected at each depth and these values were used to convert extractable soil nutrient concentrations to kg ha^{-1}. All soil samples were air-dried to a constant weight, ground with a rolling pin to break aggregates, mixed, sieved (<2 mm fraction retained), and analyzed for extractable nutrient levels (N, P, K, S, Ca, and Mg), organic C and N, pH, and EC. Total inorganic N (NH_4^+-N and NO_3^--N) and inorganic P were determined using 2.0*M* KCl [69] and modified Kelowna [87] extractions, respectively, with the extracts analyzed colorimetrically (Technicon AutoAnalyzer; Technicon Industrial Systems, Tarrytown, NY, USA). Extractable S was determined using 0.01*M* $CaCl_2$ [50] and analyzed using microwave plasma-atomic emission spectrometry (4100 MP-AES; Agilent technologies, Melbourne, Australia). Extractable K, Ca, and Mg were determined using 1.0*M* NH_4OAc [47] and analyzed using either atomic emission (K) or absorption (Ca and Mg) spectroscopy (Varian Spectra 220 Atomic Absorption Spectrometer; Varian Inc., Palo Alto, CA, USA). Total N was determined using a H_2SO_4/H_2O_2 digest [113] and analyzed colourimetrically as well. Organic N was calculated from the difference between total N and inorganic N. Total soil carbon (C) was measured using a LECO C632 Carbon Analyzer (LECO Corporation, St. Joseph, MI, USA). Soil organic C (SOC) was likewise measured [118], but following a 6 % H_2SO_3 pre-treatment to remove the inorganic C [105]. Soil pH and EC [1:2 soil suspension; soil:water on a weight basis; 46] were analyzed using a Beckman 50 pH meter (Beckman Coulter, Fullerton, CA, USA) and an Accumet AP85 pH/EC meter (Accumet, Hudson, MA, USA), respectively. Particle size distribution was determined using a Horiba

LA-950 Particle Size Distribution Analyzer (Horiba Instruments Inc., Irving, CA, USA) after pre-treatment with bleach (sodium hypochlorite) to remove SOM, followed by a 10 % solution of sodium hexametaphosphate to breakdown clay aggregates. Given the inherent micro-scale heterogeneity of soil and its confounding effect on plant nutrient availability assessments, post-harvest soil samples were not used to validate our calculated nutrient budgets. Instead, our nutrient budget forecasts, which are based on meticulous sample collection throughout the rotation, were considered to be more valuable and meaningful compared to an *a posteriori* validation using post-harvest soil nutrient extraction data with greater uncertainty.

Nutrient inputs through soil mineral weathering

Phosphorus, K, Ca, Mg are the macroelements for which mineral weathering is expected to make a substantial contribution to plant available pools over the lifespan of a SRC willow plantation, and these inputs were estimated at every site using the elemental depletion method [73]. The technique is based on the increased enrichment of immobile and recalcitrant $ZrSiO_4$ since the last glaciation and is an accurate surrogate for the weathering losses of other nutrient-bearing minerals (i.e., inputs into the plant available soil nutrient pool). At every site, a soil sample was collected from each soil horizon within the excavated classification pedon and prepared as previously stated and then additionally ground to a fine powder using a rotating ball-bearing mill. Sub-samples of the pulverized samples were sent to the Department of Earth Sciences' X-ray Laboratory at the University of Ottawa for X-ray fluorescence spectroscopic analysis (Philips PW2400; PANalytical, Almelo, The Netherlands). The measured concentrations of P, K, Ca, Mg, and Zr within each weathered horizon, along with their associated concentrations within the unweathered parent material, were used to calculate the cumulative input of each nutrient element (X_{Input}; kg ha^{-1}) into the plant available soil nutrient pool using Eq. 1, a simplified equation adapted from Melkerud et al. [73]:

$$X_{Input} = \frac{Zr_{WH}}{Zr_{PM}} \times X_{PM} - X_{WH} \times T_{WH} \times \rho b_{WH} \times 100 \quad (1)$$

where Zr_{WH} and Zr_{PM} are the percentage of Zr in the weathered horizon and parent material, respectively; X_{PM} is the percentage of element X in the parent material; X_{PM} is the percentage of element X in the weathered horizon; T_{WH} is the weathered horizon thickness (m); ρb_{WH} is the bulk density of the weathered horizon (kg m^{-3}), and 100 is a unit conversion factor. The historic annual nutrient supply rate from mineral weathering was estimated by dividing the calculated cumulative

input by the soil age [i.e., years since deglaciation; 22], although this is not necessarily either the current or future weathering rates.

Nutrient inputs through atmospheric deposition

The contribution of total atmospheric deposition to plant available soil nutrient pools through either precipitation-borne nutrients (i.e., wet deposition) or air-borne nutrients (i.e., dry deposition; DD) was estimated by measuring bulk deposition (BD) and throughfall (TF) water nutrient contents at each site during the three post-coppiced growing seasons (May to October) until harvest. Bulk deposition water samples were collected using open-ended 2 L polypropylene containers initially painted black and then white (capped with countersinked 100 cm^2 polypropylene funnels) and placed at the four corners of each replicated block, but adequately separated from the willow to avoid canopy interference. A polyethylene screen (2 mm mesh) was placed over the funnel to prevent contamination from coarse debris. With the countersunk design of the collectors, it was assumed that the BD samples strictly represented wet deposition, although this may be valid only for N, P, and S [108]. Identical containers were placed within the four SX64 variety replicate plots to collect TF water samples under the willow canopy. The variety SX64 was chosen due to its proven reliability within North American SRC plantations [62,112]. Collecting TF water samples under each willow variety canopy for comparison was cost-prohibitive and, therefore, it was assumed that SX64 was representative of all varieties. The volume of collected BD and TF samples was measured monthly, sub-sampled and refrigerated during transport back to the lab, filtered (0.05 µm; Millipore Filter Corporation Bedford, MA, USA), and then frozen until analyzed. The water samples were analyzed for their NH_4^+-N, NO_3^--N, P, K, S, Ca, and Mg concentrations in the same manner as the soil extraction samples, with the Na concentration measured using atomic emission spectroscopy (Varian Spectra 220 Atomic Absorption Spectrometer; Varian Inc., Palo Alto, CA, USA).

Growing season average compositions of precipitation and TF were calculated based on volume-weighted mean concentrations. Neither BD nor TF samples were collected during the establishment year. The contribution of BD during the establishment year was estimated using the volume of rainfall received and the average concentration of BD samples collected during the three post-coppice years. Considering the relatively small willow leaf surface area during the establishment year, any CE contributions to the nutrient budget (via TF) were assumed to be negligible. Given the circuitous nature of TF, the resultant water chemistry is complex and includes DD nutrients washed off foliage and branches. Additionally, TF samples are altered by CE processes, which can be either a nutrient source (i.e., foliar leaching) or sink (i.e., foliar absorption) as precipitation passes through the

willow canopy. The relative effects of DD and CE on the net throughfall (NTF; $NTF_{Nutrient} = TF_{Nutrient} - BD_{Nutrient}$) contribution of NH_4^+, NO_3^-, P, K, S, Ca, and Mg to the plant available nutrient pool at each site, was estimated indirectly from collected BD and TF samples using the canopy budget model [114]. This model has been widely used to successfully estimate DD and CE fluxes within a variety of canopies, based on the inert tracer Na^+ DD correction factor [108]. Specifically, the DD contribution for a given nutrient ($DD_{Nutrient}$; kg ha^{-1}) is calculated using Eq. 2:

$$DD_{Nutrient} = \frac{TF_{Na^+} + SF_{Na^+} - BD_{Na^+}}{BD_{Na^+}} \times BD_{Nutrient} \quad (2)$$

where TF_{Na+} and SF_{Na+} are the TF and stemflow sample Na^+ content (kg ha^{-1}), respectively; BD_{Na+} is the BD sample Na^+ content (kg ha^{-1}); and $BD_{Nutrient}$ is the BD sample nutrient content (kg ha^{-1}). Considering the technical difficulty associated with quantifying the cumulative stemflow nutrient flux of numerous small-diameter willow stems, along with stemflow accounting for only 2 % of gross precipitation within SRC willow plantations [67], the contribution of stemflow was assumed to be negligible (i.e., 0) when calculating $DD_{Nutrient}$ values using Equation 2. For each nutrient except N, the relative contribution of CE ($CE_{Nutrient}$) was calculated by subtracting $DD_{Nutrient}$ from $NTF_{Nutrient}$ [$CE_{Nutrient} = NTF_{Nutrient} - DD_{Nutrient}$; 12]. A positive $CE_{Nutrient}$ value indicates the willow canopy is contributing to $NTF_{Nutrient}$ flux through foliar leaching, while a negative $CE_{Nutrient}$ value points to a reduced $NTF_{Nutrient}$ flux due to foliar absorption of precipitation-borne nutrients. The canopy budget model is considered inadequate for estimating DD_N values, given the variety of atmospheric N compounds (e.g., dissolved, gaseous, and particulate), therefore DD_N was assumed to be zero, resulting in $CE_N = NTF_N$ [12].

Nutrient output through the export of above-ground willow biomass

Biomass removal from each site during coppicing after the first growing season and again during harvesting at the end of the rotation (three years post-coppice) was quantified by bundling the cut stems (including branches) within the measurement area of each varietal plot and recording their fresh weight. Numerous stem subsamples from each bundle were then dried at 65°C to a constant weight and weighed to determine moisture content. The moisture contents were used to determine the bundle oven-dry weight, in order to extrapolate the measurement plot data to a stand level (i.e., total oven-dry tonnes of biomass per hectare). The subsamples were then thoroughly milled and homogenized prior to analyzing for N, P, K, S, Ca, and Mg contents of the biomass removed from the site. Total N, P, K, Ca, and Mg contents were analytically measured following a H_2SO_4/H_2O_2 digest [113] as previously

described. Total S content was measured using a TruSpec CNS analyzer (Leco Corporation, St. Joseph, MI, USA).

Nutrient output through leaf litter, stool, and root tissue biomass

Estimates of annual nutrient output from the plant available soil nutrient pool through accumulated leaf litter nutrients at each site were taken from Hangs et al. [44]. In a separate companion study, Stadnyk [107] measured the fine and coarse root biomass of all varieties at each site and these values were supplemented with relative biomass proportions among stems, stool, and fine/coarse root fractions reported in the literature [41,95], to estimate the annual below-ground biomass within each plantation throughout the rotation. The decomposition of stool and coarse root biomass was considered to be negligible throughout the rotation [82,96], with the nutrient content of these two biomass sinks only estimated at the end of the rotation. Conversely, fine-root biomass production was estimated annually and summed. Stool and root (fine and coarse fraction) tissue samples were prepared and analyzed for N, P, K, S, Ca, and Mg concentration, following the same manner as the stem samples, to estimate nutrient immobilization within above- and below-ground willow tissues. Adequate weed control is essential for not only supporting the successful establishment and growth of SRC willow plantations [64], but also for reducing nutrient uptake by non-crop vegetation [42]. Weed control throughout the rotation was sufficient; therefore, nutrients immobilized in weeds were considered negligible and not quantified.

Nutrient output through leaching and denitrification losses

Nutrient fluxes beyond the effective willow rooting zone were measured throughout the rotation using suction lysimeters (60 kPa; SoilMoisture Equipment Corp., Santa Barbara, CA, USA) installed (60 cm depth) within the four SX64 plots at each site. As with TF collection, collecting leachate samples under each willow variety for comparison was cost-prohibitive and, therefore, it was assumed that SX64 adequately represented all varieties. Leachate volumes were measured and sub-sampled contemporaneously with the BD and TF samples and were handled and analysed in like manner. The upper limit of water volume leached through the soil profile during each growing season was estimated for each site, using a basic soil water balance model [59], and this water volume was multiplied by the leachate nutrient concentration data to provide an approximation of maximum annual nutrient leaching losses (kg ha^{-1}). Meteorological input data for the water balance model were collected at each site using a weather station (Campbell Scientific, Edmonton, AB, Canada). Lysimeter samples were not collected during the establishment year and so the leachate concentrations measured during the first

growing season post-coppice were applied to the water balance model output for the establishment year to estimate leaching losses. Nitrous oxide emissions were found to be negligible at the Saskatoon site [<<1 kg N ha^{-1}; 30] and presumably were the same for the other three sites given the negligible denitrification losses from SRC willow plantations often reported [27,34,102].

Nutrient transfers through soil organic matter mineralization, canopy exchange, leaf litter decomposition, and fine root turnover

The potential contribution of net mineralization of SOM to plant available soil N and S pools was measured using an incubation procedure [24]. Briefly, field moist soils from each site were sieved (<4 mm) and 5 g were placed in polypropylene containers and maintained at field capacity for a period of eight weeks. An incubation temperature of 15^{o}C was used to simulate the average growing season temperature among all four sites. Subsamples of the field moist soils and incubated soil samples were then prepared and extracted for inorganic N (NH_4^+-N and NO_3^--N) and S as previously stated. The potential net mineralization contributions from organic N and S were calculated by subtracting the initial extractable nutrient levels from the final extractable levels after the incubation period.

Throughfall water nutrient enrichment due to foliar leaching, as precipitation passed through the willow canopy, was quantified for each nutrient and applied to the nutrient budget whenever applicable. Unlike such immediate nutrient transfer to the plant available nutrient pools from living tissue, most nutrients within fallen leaves are immobilized in the organic material and consequently, are not readily available for plant uptake until re-mineralized. Consequently, litterbags were used to measure the rate of leaf litter decomposition and nutrient release throughout the rotation. Using the estimated nutrient release rate constants and accumulated leaf litter biomass over the four-year rotation, the contribution of leaf litter nutrient release to the plant available soil nutrient pools were calculated [44]. Based on the litterbag results, the leaf litter cohorts considered in our nutrient budget calculations during the rotation were nutrient release from: three years of establishment year leaf litter (i.e., pre-coppice leaf biomass); two years of first year post-coppice leaf litter; and, one year from the second year post-coppice leaf litter. The remaining nutrient release contributions from the first to third year post-coppice leaf litter were associated with the second rotation [44].

Below-ground biomass nutrient sinks (e.g., stool, fine and coarse root nutrient contents) and annual nutrient transfers from fine-root turnover to the plant available nutrient pools at each site were estimated using relative proportion and minirhizotron data collected during the rotation [107] and also supplemented with literature values [86,95,96]. Nutrient resorption during fine root senescence was

assumed to be negligible [4,79]; therefore, all fine root nutrients were considered available for cycling back into the soil.

Statistical analyses

Means comparisons of measured variables were performed using least significant differences (LSD; Tukey-Kramer's method of multiple comparison) at a significance level of 0.05 using PROC MIXED in SAS [65; version 9.2; SAS Institute, Cary, NC, USA], with groupings performed with the pdmix800 SAS macro [101]. The effects of variety were considered fixed, while those of site and replicate (nested within site) were considered random. Normality of distributions (PROC UNIVARIATE) and homogeneity of variances (Bartlett's test) of all data sets were verified, and when required, the data were Log_{10} transformed prior to analysis.

Results

Comparing baseline soil nutrient availability among plantations

For all nutrients except P, the soil nutrient availability was least at Prince Albert and similar among the other sites (Table 2). Likewise, the measured levels of pH, organic C and N were lowest at Prince Albert, compared with the finer-textured lower bulk density soils at the other sites, which supports the lowest Agriculture Capability Classification rating of the sandy Prince Albert soil (Table 1). The relative ranking of initial extractable levels of soil nutrients among the four sites was Ca > Mg > K > S > N > P (Table 2).

Inputs into the plant available soil nutrient pool

The historic soil mineral weathering supply of P, K, Ca, and Mg to the plant available nutrient pool was minor in proportion to their initial extractable levels (i.e., <<1 %; Tables 2 and 3). Increasing leaf surface area as the plantations aged (data not shown), resulted in a significant (P <0.05) site × year effect among the measured atmospheric deposition (BD + DD) and CE variables, so the mean cumulative values (and associated standard error) after the three-year post-coppice measurement period prior to harvesting were reported (Table 4). Atmospheric deposition of nutrients during the three years were 32.6, 4.3, 21.3, 27.0, 39.2, and 14.1 kg ha^{-1} of N, P, K, S, Ca, and Mg, respectively, with the majority of nutrients derived from wet deposition. Canopy exchange reactions were greatest for N, resulting in direct foliar uptake of 21.0 kg N ha^{-1} from atmospheric deposition after three years, leading to negative NTF values and much less contribution of atmospheric N to the soil nutrient pools compared with the other nutrients having positive NTF balances (Table 4). Specifically, strong foliar

absorption of atmospheric N (approximately 8× greater absorption of NH_4^+-N than NO_3^--N; data not shown) by the willow canopy contrasted with the foliar leaching of K and to a lesser extent P and Ca. Atmospheric S and Mg depositions were essentially non-reactive with the willow canopy, resulting in TF contributions to the plant available soil nutrient pool strictly from wet and dry deposition (Table 4). The combined effects of atmospheric deposition and CE on plant available nutrient pools are represented in the measured TF values of 11.6, 7.7, 31.9, 26, 43.1, and 13.6 kg ha^{-1} of N, P, K, S, Ca, and Mg, respectively.

Outputs from the plant available soil nutrient pool

The average stem biomass removed from the four sites at time of coppicing and harvest was 0.6 and 18.4 Mg ha^{-1}, respectively (Table 5), with the range in harvested biomass among willow varieties and sites three-years after coppicing of 2.8-41.2 Mg ha^{-1} [40]. The nutrients exported from each site through the removal of willow stems, during coppicing following the establishment year in addition to harvesting the willow stems averaged 16, 2, 12, 3, 34, and 5 kg ha^{-1} $year^{-1}$ of N, P, K, S, Ca, and Mg, respectively (Table 5). With the exception of harvested stem P content at Estevan, the trend in nutrient removals offsite during coppicing and harvesting followed the pattern of biomass productivity, with Prince Albert and Estevan having the largest amount of stem nutrients immobilized after the establishment year and third-year after coppicing, respectively (Table 5). The average leaf litter nutrient content among the willow varieties and sites was 80.8, 14.6, 108.1, 24.5, 255.7, and 41.2 kg ha^{-1} of N, P, K, S, Ca, and Mg, respectively [44]. Additional sinks of plant available soil nutrients included the below-ground willow biomass that consisted of stools and fine and coarse roots, which were 1.2, 10.5, 0.8 Mg ha^{-1}, respectively, after the initial four-year rotation among willow varieties and sites, with the trend in nutrient immobilization related to the relative biomass of these below-ground tissues (Table 6). Among the sites, the average amount of nutrients tied up in stools was 4.2, 0.7, 1.5, 1.1, 1.9, and 0.9 kg ha^{-1} of N, P, K, S, Ca, and Mg, respectively. The average amount of nutrients tied up in fine and coarse roots after the initial rotation was 148.9, 40.1, 58.2, 38.2, 50.4, and 39.2 kg ha^{-1} of N, P, K, S, Ca, and Mg, respectively, greater than 92 % of which were contained within the fine root fraction (Table 6). As previously mentioned, nitrous oxide emissions were assumed to be negligible at our study sites, so the only below-ground loss of nutrients measured in this study was leaching. Average nutrient leaching losses across sites during the four-year rotation were 6.8, 0.4, 1.0, 22.5, 45.6, and 31.6 kg ha^{-1} of N, P, K, S, Ca, and Mg, respectively (Table 7). Nitrate comprised 85 % of the N leached (data not shown) and there were no discernible trends in nutrient leaching among sites.

Transfers into the plant available soil nutrient pool

The contribution of potential net N and S mineralization during each growing season averaged 45 and 28 kg ha^{-1} yr^{-1}, respectively (Table 3). A large degree of foliar absorption of atmospheric N precluded foliar leaching of either NH_4^+-N or NO_3^--N (89 % of the inorganic N intercepted and retained by the willow canopy was NH_4^+-N; data not shown). Canopy exchange through foliar leaching contributed to soil K, P, and Ca availability during the four-year rotation, providing 3.4, 10.6, and 3.8 kg ha^{-1}, respectively, while S and Mg atmospheric depositions were essentially non-reactive with the willow canopy (Table 4). Throughout the rotation, the willow canopy acted as a sink for atmospheric N, while 69, 59, and 20 % of the NTF flux of P, K, and Ca, respectively, originated from canopy leaching, and S and Mg were entirely DD with negligible canopy interactions. The average contribution of nutrients from leaf litter decomposition during the rotation across varieties and sites was 21.5, 3.9, 47.3, 10.5, 112.0, and 18.5 kg ha^{-1} of N, P, K, S, Ca, and Mg, respectively, with the Estevan soil receiving 72 % more nutrients from decomposing leaf litter during the rotation than other sites [44]. Decomposing fine root biomass contributed 49.9, 12.3, 17.7, 11.7, 15.4, and 12.0 kg ha^{-1} of N, P, K, S, Ca, and Mg, respectively, with 41 % less nutrient transfers from fine root decomposition at Estevan compared to the other sites (Table 8).

Soil nutrient budget after initial rotation

Nitrogen

At the end of the initial four-year rotation, soil N outputs were greater than soil N inputs, resulting in an average removal (i.e., budget deficit) of 17 kg N ha^{-1} across varieties and sites (Table 9). Although there were no differences (P >0.05) in N removals among the sites, when the net soil nutrient balance was expressed as a percent change from the initial extractable pool level, there was a 24 % depletion in soil N reserve, with the largest soil N depletion occurring at Prince Albert (Table 9). The relative contribution of SOM mineralization, CE, leaf litter decomposition, and fine root turnover transfers to plant available soil N supply was 72, 0, 8, and 20 %, respectively; compared to the N sinks of below-ground biomass (51 %), leaf litter (26 %), harvested stems (21 %), and leaching (2 %; Table 10).

Phosphorus

Soil P outputs during the rotation were greater than soil P inputs, resulting in an average removal of 39 kg P ha^{-1} across varieties and sites; representing a 105 % depletion in soil P reserve (Tables 9 and 10). The calculated soil P depletion is affected by the disproportionate influence of the Birch Hills soil P

budget, which had a calculated depletion of 243 % in soil P reserves compared with 54 % for the other three sites, with the smallest P deficit observed at Estevan (Table 9). The relative contribution of soil mineral weathering and atmospheric deposition to soil P supply was 3 and 97 %, respectively (Table 10), although there may also be some P addition from mineralization of soil organic P that was not measured in this study. The relative contribution of CE, leaf litter decomposition, and fine root turnover transfers to soil P supply was 17, 20, and 63 %, respectively; compared to the P sinks of below-ground biomass (62 %), leaf litter (23 %), harvested stems (14 %), and leaching (1%; Table 10).

Potassium

Soil K outputs during the rotation were greater than soil K inputs, resulting in an average deficit of 112 kg K ha^{-1} across varieties and sites; representing a 9 % depletion in soil K reserve (Tables 9 and 10). The largest K deficit occurred at Birch Hills and the smallest soil K deficit was at Saskatoon (Table 9). The relative contribution of soil mineral weathering and atmospheric deposition to soil K supply was 36 and 64 %, respectively (Table 10). The relative contribution of CE, leaf litter decomposition, and fine root turnover transfers to soil K supply was 14, 63, and 23 %, respectively; compared to the K sinks of below-ground biomass (27 %), leaf litter (51 %), harvested stems (21 %), and leaching (1 %; Table 10).

Sulfur

Inputs to the plant available soil S reserve during the rotation were greater than the outputs, resulting in an average surplus of 73 kg S ha^{-1} across varieties and sites; representing a 17 % enrichment in soil S supply (Tables 9 and 10). The largest surpluses occurred at Estevan and Saskatoon, with the relative enrichment at Prince Albert 2.5× greater than the other sites after four years (Table 9). The relative contribution of SOM mineralization, CE, leaf litter decomposition, and fine root turnover transfers to soil S supply was 83, 0, 8, and 9 %, respectively; compared to the S sinks of below-ground biomass (42 %), leaf litter (26 %), harvested stems (11 %), and leaching (21 %; Table 10).

Calcium

Soil Ca outputs were greater than soil Ca inputs after four years, resulting in an average removal of 271 kg Ca ha^{-1} across varieties and sites; representing a 2 % depletion in the measured soil Ca reserve (Tables 9 and 10). There were no differences (P >0.05) in calculated soil Ca deficit or depletion among the sites (Table 9). The relative contribution of soil mineral weathering and atmospheric deposition to soil Ca supply was 45 and 55 %, respectively (Table 10). The relative contribution of

CE, leaf litter decomposition, and fine root turnover transfers to soil Ca supply was 3, 85, and 12 %, respectively; compared to the Ca sinks of below-ground biomass (11 %), leaf litter (53 %), harvested stems (27 %), and leaching (9 %; Table 10).

Magnesium

Soil Mg outputs were greater than soil Mg inputs, resulting in an average deficit of 74 kg Mg ha^{-1} across varieties and sites; representing a 2 % depletion in soil Mg reserve after four years (Table 10). The only difference in calculated Mg deficit among sites was between Birch Hills and Prince Albert, with Saskatoon having the smallest soil Mg depletion (Table 9). The relative contribution of soil mineral weathering and atmospheric deposition to soil Mg supply was 42 and 58 %, respectively (Table 10). The relative contribution of CE, leaf litter decomposition, and fine root turnover transfers to soil Mg supply was 0, 60, and 40 %, respectively; compared to the Mg sinks of below-ground biomass (31 %), leaf litter (32 %), harvested stems (14 %), and leaching (24 %; Table 10).

Discussion

Baseline soil fertility at each willow plantation

The soil properties at each site were within the recommend range for supporting SRC willow growth [1,56]. The observed differences in soil type and associated properties among the four sites are largely related to the varying soil parent materials, along with past management practices, and historical climate/vegetation regime [7]. Three of the sites (Birch Hills, Estevan, and Saskatoon) were developed on moderately fine to fine textured, glacio-lacustrine deposits, while the Prince Albert soil was developed on coarse to moderately coarse textured glacio-fluvial deposits. Consequently, although there were measured differences in the inherent fertility among soils (Table 2), the Class 5 soil at Prince Albert was the poorest quality soil tested. For example, SOM content (i.e., organic C and N) is often considered a key 'soil quality' measure, given its intimate association with essential physical, chemical, and biological properties controlling soil productivity [38,124]. The lowest SOM content of the Prince Albert soil, therefore, is an important indicator of the differences in long-term soil nutrient availability, especially soil N and S. Likewise, coarse textured soils have comparatively less P, K, Ca, and Mg-bearing minerals, along with reduced sorption capacity, compared with finer textured soils. However, past management practices can also play a critical role in soil nutrient supply, as evidenced by the greater soil P availability at Prince Albert (Table 2), which resulted from repeated applications of high fertilizer P rates prior to establishing the willow plantation.

Inputs into the plant available soil nutrient pool

Soil mineral weathering

The contributions of P, K, Ca, and Mg to the plant available nutrient pool from soil mineral weathering are consistent with those reported elsewhere [73,119], but the relative importance of these contributions to the overall nutrient budget were negligible compared to their initial extractable levels (i.e., <0.1 %; Tables 2 and 3). However, it is possible that the relative proportion of mineral weathering inputs may have been underestimated as afforested agricultural soil can have augmented mineral weathering rates, presumably due to greater root biomass favouring increased production of acidic root exudates and symbiotic mycorrhizal associations (e.g., hybrid poplar; Lafleur et al., 2013).

Atmospheric deposition

The measured nutrient inputs via atmospheric deposition were consistent with literature values [12,37] and similar to the other inputs. Atmospheric deposition improved soil N availability relative to its initial extractable level more than other nutrients (approximately 10 kg N ha^{-1} yr^{-1}; Tables 2 and 4). Ammonium-N was the predominant inorganic N form in the bulk deposition samples (data not shown), which agrees with the finding of Lovett and Lindberg [66]. The lack of significant difference (P >0.05) in measured BD (collectors located outside of the plantation) nutrient concentrations over the four-year rotation contrasted with the increased DD (collectors located within the plantation) nutrient concentrations as the plantations aged and developed greater leaf surface area (data not shown), demonstrates the increased capacity of the developing willow canopy to filter the air, thereby capturing additional nitrogenous compounds contained in airborne particles or gases.

Outputs from the plant available soil nutrient pool

Harvested stem nutrients

When corrected for differences in annual stem biomass production, the annual nutrient removal rates contained within harvested stem biomass are similar to other studies [2,29,52,55,63,83]. Under conditions of adequate soil fertility, willow productivity is primarily controlled by moisture availability and temperature [61]; therefore, it is not surprising that our measured yields were lower than typical willow yields reported in the literature. The relatively low willow productivity observed at our sites is typical within the province [29,78] and simply reflects the less favourable growing conditions in Saskatchewan compared to other regions [e.g., 35,93,104]. The significant (P <0.05) variety × site × year interaction effects on stem nutrient contents were primarily due to the underlying differences in

willow productivity among varieties and sites (CV of 46 %; Table 5) and to a lesser extent the differences in stem nutrient concentrations [average CV of 26 % among nutrients; 40].

Numerous authors over the last several decades have referred to SRC willow as a nutrient demanding crop; however, we feel that it is prudent to put the nutrient use efficiency characteristics of willow in perspective by noting that despite the existence of large varietal differences of nutrient use efficiency among willow varieties [i.e., kg nutrient Mg biomass^{-1}; 112,120], relative to both conventional agricultural crops and alternative biomass energy crops (e.g., *Miscanthus*, *Panicum*, *Zea Mays*, *and Brassica spp.*), willow can be successfully grown with a fraction of the nutrients, thereby also providing a higher net energy ratio [14,58,122]. For example, a common four-year canola-wheat rotation in Saskatchewan produces approximately 9.5 Mg ha^{-1} of harvested biomass, while removing approximately 400 (N), 100 (P), 200 (K), 75 (S), 130 (Ca), and 50 (Mg) kg ha^{-1} from the soil [19], compared to the 66, 10, 48, 11, 136, and 18 kg ha^{-1} of N, P, K, S, Ca, and Mg, respectively, required to produce approximately 19 Mg ha^{-1} of harvested willow biomass in this study (Table 5). Our average willow yield after four years doubled the biomass produced by a typical annual crop rotation over the same period, but required a fraction of the nutrients. Specifically, the nutrient use efficiency of willow in this study was 12 (N), 21 (P), 8 (K), 15 (S), 2 (Ca), and 6 (Mg) × greater than a canola-wheat rotation, resulting in relative decreases in soil nutrient removals of 84 (N), 90 (P), 76 (K), 86 (S), 3 (Ca), and 64 (Mg) percent after four years compared to growing these traditional agronomic crops [40].

Leaf litter and below-ground biomass nutrients

The biomass and N, P, K, S, Ca, and Mg concentration estimates of willow stool, fine and coarse root tissues in this study are within the range of values reported in the literature [51,68,81,86,94-96,125]. Although only accounting for approximately 29 % of the above-ground biomass after four years [44; Table 5], willow leaf litter was the largest above-ground sink of soil nutrients, with the relative percentage of above-ground N, P, K, S, Ca, and Mg immobilized in leaves being 56, 53, 67, 69, 64, and 69, respectively [44; Table 5]. The average total above- and below-ground biomass productivity of the six willow varieties across the four sites at the end of the four-year rotation was approximately 40 Mg ha^{-1}; with approximately ⅓ of the C allocated to below-ground biomass (32 %) and the remaining 19 and 49 % apportioned to leaves and stems, respectively [44; Tables 5 and 6]. Furthermore, the majority of immobilized N, P, and S was in the below-ground biomass, while the majority of K, Ca, and Mg was present in the above-ground biomass, primarily the leaf litter. The bulk of both biomass (84 %) and nutrient content (95 %) dedicated to below-ground tissue were associated

with fine roots (Table 8), which highlights the relative importance of the fine root fraction in SRC willow production systems [96].

Nutrient leaching

The effect of site disturbance and minimal vegetation cover attendant with SRC willow establishment, especially on previously agricultural land, can often result in appreciable nutrient leaching losses [29,56,77,102]. Such short-term losses, however, are offset by smaller losses during the 20+ year lifespan of SRC willow systems, compared to characteristic nutrient leaching losses incurred with annual crop production systems over the same time frame [36]. Given the similarity in pre- and post-planting management among the four sites in this study, it was assumed that the site disturbance differences among sites were negligible. The estimated nutrient leaching losses during the initial four-year rotation are in agreement with other studies [10,77,83], albeit at the lower end of available data in the literature. The relatively minor leaching losses observed are no doubt related to the semi-arid conditions in Saskatchewan, but also the absence of any nutrient-laden amendments within this study compared to other published work. The majority of previous SRC willow leaching studies strictly examined N and P, because of their association with non-point source pollution effects on proximal water bodies. In this study, leaching of N, P, K, S, Ca, and Mg primarily occurred during the establishment year and first year-post-coppice; with the proportion of total nutrients leached decreasing each year of the rotation at all sites and more than 90% occurring during the spring period between snowmelt and bud burst (data not shown). Similar establishment year, along with inter- and intra-seasonal trends, have been reported previously [36,83,102] and presumably are consequence of reduced soil water and nutrient demand due to a combination of an undeveloped root system during the first two years, along with delayed root activity and associated water and nutrient uptake prior to bud break each spring, when early season growth is primarily supported by nutrient supply translocated internally from perennial organs [32,74,117]. The moisture deficit during each growing season was manifest in the lack of percolating water through the soil profile during the summer months, which frequently resulted in no sample collection within lysimeters, as has been reported elsewhere [45].

For every nutrient except Mg, the leaching losses from the plant available nutrient pool were more than compensated for by atmospheric deposition (Tables 4 and 7). Given the extensive deep-rooted fibrous perennial root system of willow and high rates of canopy interception and evapotranspiration, there is minimal percolation of precipitation through the soil profile during the growing season and, therefore, can be successfully used as a vegetation filter for wastewater management practices [16,25,102]. The measured N leaching losses after four years at Estevan were

3.5× larger than the other sites, but given the more favourable soil moisture and nutrient conditions at Estevan such increased N leaching is to be expected [25]. The remaining trends in nutrient leaching losses among sites are primarily attributable to their different soil types (Table 2). Specifically, P leaching was greatest at Prince Albert and this reflects the much larger residual soil P pool in that soil. The greater leaching losses of base cations (e.g., K, Ca, and Mg) and S observed at Prince Albert is due to the lower cation-exchange capacity (data not shown) and organic matter content of this sandy soil, which was not as capable of retaining nutrient ions within its profile. Base cation leaching is often cited to explain the relative decrease in soil pH following land conversion to SRC willow; however, give the semi-arid climate of Saskatchewan and phreatophytic nature of willow, leaching accounted for less than 10 % of base cation removal from soil in our study, with the remainder sequestered in plant tissues, 53 % of which was located in leaf litter [44; Tables 5, 6, and 7].

Despite its limited nutrient retention capacity, the inherently poor N supplying soil helps to explain the minimal N leaching losses at Prince Albert (Table 7). Although being the highest ranked agricultural soil of our study, the measured N leaching losses at Birch Hills were the same as the least fertile soil at Prince Albert and this is attributed to N uptake by non-crop vegetation. Although vegetation management during the rotation was adequate for all four sites, Birch Hills received the least weed control of all sites because of logistical constraints. Consequently, during the initial two years prior to canopy closure, there was an understory component consisting of volunteer canola (previous crop; *Brassica napus* L., cv. Invigor 2733), along with Canada thistle (*Cirsium arvense*) that blanketed the plantation until it was eventually shaded out by the overstorey willow. Meanwhile, this non-crop component probably acted as a sink for available soil N that would have otherwise been leached out of the system at Birch Hills, as observed with Estevan and Saskatoon with soils of similar N supplying power (Tables 2 and 7).

While N uptake by weeds is lost to willow uptake that year, the experience at Birch Hills raises an interesting point. When trying to manage for long-term site sustainability, maintaining a vegetation cover on a site is advantageous in minimizing N lost from the ecosystem via N loss pathways (e.g., erosion, leaching, and denitrification), especially on N-deficient sites such as Prince Albert. However, non-crop species are known to have a detrimental effect on the establishment and growth of planted willow. Perhaps a synergism can exist by introducing a non-competitive underseeded perennial cover-crop prior to plantation establishment, which will not only act as a temporary nutrient sink until the willow becomes established, but also control the more noxious annual weeds. Adiele and Volk [3] showed that white clover (*Trifolium repens*) can successfully reduce both soil erosion and suppressed weed growth during the establishment year without affecting willow growth. Although leaching losses

were not assessed in their study, the ability of white clover to assimilate soil inorganic N when available, despite its ability to fix atmospheric N_2, is apparent [39] and, therefore, possibly represents an effective management tool balancing the needs of the willow with the long-term soil nutrient budgets. Underseeding the SRC willow with a non-competitive leguminous perennial is unquestionably more advantageous compared to underseeding with antagonistic competitive grasses that can decrease willow productivity [103].

Transfers into the plant available soil nutrient pool

Soil organic matter mineralization

The pattern of soil N and S mineralization contributions to nutrient supply among soil types are primarily related to the relative differences in SOM content. Nevertheless, the similarity in S mineralization potential between the soils at Birch Hills (highest SOM content) and Prince Albert (lowest SOM content) is surprising, although the indefinite relationship between S mineralization and SOM content has been known for some time [123] and may be a function of relatively low sulfatase activity in the Birch Hills soil [111]. The measured soil N and S mineralization rates are typical for Saskatchewan soils [92], with these annual inputs relatively more important for N compared to S, representing an average of 59 % of the initial extractable N across the sites, compared with only 8 % for S (Tables 2 and 3).

Leaf litter decomposition and fine root turnover

Modelling efforts aimed at estimating the climate change mitigation potential of SRC willow plantations are highly dependent on reliable input parameters; in particular, litter decomposition data for predicting the magnitude of C sequestration in these plantations over the long-term [6,96]. Additionally, the agronomic significance of immobilized leaf litter nutrient cycling, within the context of plantation sustainability and fertility management, has been recognized for some time [31]. The decomposition of plant tissue (e.g., leaf litter or fine root turnover) is a primary mechanism for C and nutrient cycling within most terrestrial ecosystems [13,96] and SRC willow plantations are certainly no exception. Our estimates of leaf and root litter nutrient cycling are at the lower end of literature values, but this is primarily a function of the lower biomass production at our plantations. Regardless, our findings support the contention that nutrient cycling from leaf litter decomposition and fine root turnover are important nutrient cycling mechanisms that help to satisfy the nutritional demands of SRC willow plantations [21,32,54,95]. The Saskatoon soil received 65% less nutrient contributions from leaf litter, but 26% more nutrient contributions from fine root turnover compared to the other sites [44;

Table 8] and this is primarily a function of the difference in biomass allocation (i.e., root growth favoured) under the drier growing season conditions at Saskatoon throughout the rotation (Tables 5 and 6). The significant (P <0.05) variety × site interaction effect on leaf litter and fine root turnover nutrient additions were primarily due to differences in biomass instead of variation in tissue nutrient concentrations (CV data not shown). The key factors influencing leaf litter decomposition and attendant nutrient release in this study were leaf litter quality, moisture availability, and soil quality [44], while the characteristically rapid turnover and decomposition rates of willow fine roots contribute significantly to nutrient cycling (i.e., alternating between a nutrient source and sink); thus preserving nutrients within the production system, particularly fertilizer N [42].

Canopy exchange

When TF measurements are used to quantify atmospheric deposition contributions to plant available nutrient pools, it is important to distinguish between atmospheric nutrients and intrasystem nutrient transfers recycled through CE. The canopy budget model was useful in determining the relative importance of DD and CE contribution to NTF and their proportional influence varied depending on the nutrient. The influence of DD and CE increased each year of the rotation at all sites for all nutrients (data not shown) and this is presumably due to increasing leaf surface area as the willow canopy matured. The CE trends observed in this study, namely foliar consumption of atmospheric N (dominated by NH_4^+-N), foliar leaching of P, K, and Ca, and strictly DD contributions of S and Mg, are commonly reported in the literature [28,72,83,108]. There were no significant differences (P >0.05) among sites for any estimated canopy variable and while this is not surprising considering only one variety was examined, it does point to the lack of genotype × environment effect on canopy-atmosphere interactions for the *S. miyabeana* variety used, despite large differences in total growing season precipitation and leaf biomass among sites across a broad pedoclimatic gradient [44; Table 1].

Soil nutrient budget after initial rotation

Nitrogen

Although there were no significant differences (P >0.05) in measured plant available soil N pool deficits among the four sites after the initial rotation (Table 9), when the net soil N balance was expressed as a percent change in initial extractable N pool level, the Prince Albert soil experienced the greatest percent depletion due to the relatively poor N supply power of this coarse-textured soil (Table 2). Removing approximately 25 % of the soil N reserve during the initial rotation is substantial, especially when expecting a 30 % increase in above- and below-ground productivity (with a

concomitant increased nutrient demand) during subsequent rotations [81,116]. However, it is important to recall that more than half of the leaf litter nutrients immobilized during the first rotation were not included in the budget, with the remaining leaf litter nutrient contributions released during the second rotation [44]. Consequently, assuming a 30% increase in nutrient demand during the second rotation compared to the first, the residual leaf litter nutrients from the first rotation will provide approximately 42% of the soil N demand during the second rotation. Likewise, N will be cycled from fine root turnover immobilized during the first rotation and will provide approximately 49 kg N ha^{-1} over the next two rotations, assuming a 20 % $year^{-1}$ release [86] and 89 % decomposition limit value [96].

Although fine roots represent a larger sink for immobilized nutrients within SRC willow plantations than leaf litter [44; Table 6], fine roots have a slower decomposition rate and, therefore, represent a more slow-release nutrient source over time. Clearly, such nutrient cycling requires consistent annual mineralization rates, but presumably, growing season conditions favourable for willow growth and associated nutrient demand will likewise be favourable for the decomposer community activity. The capacity of leaf litter N cycling to meet the nutritional requirements of subsequent rotations to such a large degree has been recognized previously [21,32], and when coupled with nutrient additions from fine root turnover, soil mineralization, atmospheric deposition, foliar nutrient resorption, along with the relatively low nutrient demanding nature of willow, it is not surprising to see the lack of willow growth response to added fertilizer often reported in the literature, especially when grown on good agricultural soils [42].

Despite the efficient N cycle within these SRC willow plantations, with minimal system losses from these sites through either denitrification [30] or leaching (Table 7), it is prudent to assume that a portion of recycled N will be immobilized by the microbial community each year; ultimately becoming a relatively unavailable recalcitrant stable organic N fraction. Additionally, considering the expected lifespan of a willow plantation is seven rotations (Heller et al., 2003) and changes will occur in above- and below-ground growth allocation patterns in later rotations, as more biomass is allocated to stem growth at the expense of reduced root and leaf growth [52,121], there will reduced N cycling from these tissues. Consequently, we would agree with the conventional practice of applying sufficient fertilizer to compensate for nutrient losses associated with harvesting willow stems [1,32], which would equate to approximately 25 kg N ha^{-1} yr^{-1} with our current production levels.

Phosphorus

The smallest soil P deficit occurred at Estevan and probably is due to reduced P sequestered in leaf and fine root biomass compared to the other sites [44; Table 6]. The most intriguing observation in this study was the >200 % decrease in initial extractable soil P pool calculated at Birch Hills (Table 9). At this site, approximately 55 kg P ha^{-1} were required to produce approximately 41 Mg ha^{-1} of above- and below-ground biomass over four years [44; Tables 5 and 6], despite an initial available soil P level of only 16 kg ha^{-1} (Table 2). The Birch Hills site was the only willow plantation established immediately following an annual crop production year. Instead of being previously fallowed like the other three sites, the Birch Hills plantation was planted following a high-yielding canola crop that would have depleted soil P levels and contributed to the calculated soil P deficiency (approximately 10 kg P ha^{-1} yr^{-1}) during the first rotation. It seems reasonable to assume that the apparent soil P deficit at Birch Hills was satisfied by the well-known ability of mycorrhizae to augment soil mineral weathering under conditions of low P availability given the synergism between these beneficial root-associated fungi and SRC willow [23,85].

As with the deferred N release from decomposing leaf litter, P immobilized during the first rotation within leaf litter will provide 36 % of the soil P demand during the second rotation, while fine root turnover will supply approximately 19 kg P ha^{-1} over the next two rotations. The largest calculated depletion in soil nutrient reserves among the sites after the first rotation occurred with soil P and maintaining adequate soil P levels is important for not only supporting long-term site productivity, but also minimizing risk of disease and herbivory [55]. In addition to conventional inorganic fertilizer amendments, returning residual wood ash back to the plantation can effectively restore soil P supply [84,103]. Wastewater sludge and pig slurry are other alternative fertilizer amendment successfully used to improve soil P fertility within SRC willow plantations, although care must be taken in choosing appropriate application rate and soil type to prevent groundwater contamination [20,25,63]. Given its diffusion-limited nature in soil, P is relative immobile compared to other nutrients and, therefore, fertilizer P additions (inorganic or organic) will typically accumulate near the surface, which is proximally ideal in terms of availability to the majority of willow roots. The degree of soil P depletion observed among the four sites and projected need for fertilizer P going forward is surprising given the relatively low P demand of willow often reported in the literature, even on sandy soil with inherently low levels of P-bearing minerals [e.g., 15]. Using data from our study, P inputs from soil mineral weathering and atmospheric additions are inadequate to meet the soil P demand of the growing willow and applications of 25 kg P ha^{-1} $year^{-1}$ may be required to maintain the soil P supply under the

expected willow growth and internal P cycling regime. Some consideration of the possible contributions from organic P mineralization and enhanced P solubilisation and uptake through beneficial fungal relationships should be considered in future studies of P cycling in SRW willow systems on the prairies.

Potassium

The consistently large K content in the willow biomass growing at Birch Hills relative to other sites explains the greatest soil K deficit observed there; however, the percent depletion in soil K at Birch Hills was not significantly different (P >0.05) than Estevan or Prince Albert (Table 9). The smallest percent soil K depletion occurred at Saskatoon and can be attributed to not only its relatively poor biomass production, but also the abundant K-bearing clay minerals in Saskatoon, which provided the largest plant available soil K level of all sites (Table 2). Decomposing leaf litter from the first rotation will provide 81 % of the soil K demand during the second rotation, while fine root turnover will supply approximately 27 kg K ha^{-1} over the next two rotations. Despite relatively large soil K deficits over multiple rotations, a sizable soil K reserve helps to mitigate the impact, as observed elsewhere [49,57,63]. Returning wood ash to the site can also assist in maintaining soil K fertility [84,103]. The only difference in calculated plant available soil nutrient pools among the six willow varieties across the four sites occurred with less K removed from soil after four years by the variety Fish Creek compared to Canastota (data not shown). Although there were significant (P <0.05) variety × site effects on biomass production (Tables 5 and 6), the relative lack of observed differences in soil nutrient withdrawal among varieties, evidently must be due to the offsetting significant (P <0.05) variety × site effects on above- and below-ground tissue nutrient concentrations (i.e., nutrient use efficiency) concomitant with different phenotypic responses to productivity gradients [40].

Sulfur

Sulfur was the only nutrient with a calculated soil supply surplus after the initial rotation, with the largest surplus at Estevan primarily due to a combination of less S immobilized in fine roots, but also greater S release from SOM mineralization (Tables 3 and 6). The largest percent soil S enrichment occurred at Prince Albert and is not surprising given the inherently poor S supplying ability of this sandy soil (Tables 2 and 3). Although there was no significant difference (P >0.05) in atmospheric S deposition among the sites (average of 8.6 kg S yr^{-1}; data not shown), the proportional contribution of atmospheric deposition to the plant available soil S supply was greater for the Prince Albert soil due to its smaller initial S level. The first rotation leaf litter will provide 47 % of the soil S demand during the

second rotation, while fine root turnover will supply approximately 18 kg S ha^{-1} over the next two rotations. Given the measured soil S surplus at each site, along with the apparent low S-demanding nature of the willow varieties examined, we are not concerned about soil S supplies limiting willow growth at any site over the long-term. With limited information available regarding S cycling from other regions, more investigations of S dynamics within SRC willow plantations are welcomed.

Calcium

Despite having the largest calculated nutrient deficits after four years, the lack of calculated differences in available soil Ca among the sites is indicative of the calcareous nature of Saskatchewan soils, which have abundant plant available Ca (Table 2). Moreover, the first rotation leaf litter is predicted to provide 85 % of the soil Ca demand during the second rotation, while fine root turnover will supply approximately 24 kg Ca ha^{-1} over the next two rotations. The largest measured nutrient removals from soil reserves in this study occurred with Ca, however, chronic large exports of soil Ca over multiple rotations will have minor impact on the long-term soil Ca supply for the majority of Saskatchewan soils and this is consistent with other reports [49,57,63]. Specifically, the soil parent material within the bottom ⅔ of the province is glacial drift derived from Devonian sedimentary bedrock, which primarily consists of limestone and dolomite, resulting in abundant Ca and Mg supply [90,91].

Magnesium

The lone dissimilarity in available soil Mg deficits among sites occurred between Birch Hills and Prince Albert and the larger deficit in Birch Hills was due to its greater productivity and associated Mg sequestered in above-and below-ground tissues [44; Tables 2, 5, and 6]. Similar with soil K, the smallest percent soil Mg depletion at Saskatoon can be attributed to the relatively poor productivity during the rotation and its soil clay mineralogy providing the largest Mg supply (Table 2). In addition, the first rotation leaf litter will provide 63 % of the soil Mg demand during the second rotation, while fine root turnover will supply approximately 18 kg Ca ha^{-1} over the next two rotations. Depletion of soil Mg reserves were second only to soil Ca depletion, but similar to Ca, the majority of Saskatchewan soils have abundant Mg supply that should support multiple SRC willow rotations. Although such ample soil Mg supply is common [49,63], it is certainly not universal. For example Kahle et al. [57] expressed concern regarding the effect of multiple SRC willow rotations on sustainable soil Mg supply; however, their extractable soil Mg level was approximately 350× less than the average extractable level of the soils in our study.

Long-term soil fertility and SRC willow sustainability

Future energy crop production is most likely to occur on marginal agricultural land in order to avoid conflict with food production and compromising food security [9,115]. Previous studies have highlighted the ability of willow to grow with minimal soil nutrient demand on a variety of soil types [88,103,109] and our study was no exception, with some varieties achieving annual production greater than 10 Mg ha^{-1} yr^{-1} on the sandy soil at Prince Albert without fertilization during the rotation [40]. However, our results indicate that despite the relatively low nutrient-demanding nature of willow, long-term soil productivity will need to be managed with nutrient amendments, particularly N and P, albeit at application rates that are a fraction of what is required to sustain the growth of annual crops or contemporary alternative biomass energy crops. Furthermore, unlike contemporary alternative bioenergy crops, requiring chronic removals of all above-ground biomass, the SRC willow in this study cycled more than seven tonnes of leaf litter biomass during the initial rotation, which will play an important role in both long-term nutrient cycling and augmenting SOM levels [44].

There are many biotic and abiotic factors that can have a deleterious impact on SRC willow plantation productivity, including: drought and winter kill, animal and insect herbivory, disease, and competition from non-crop vegetation. Given the many uncontrollable factors that can potentially affect plantation productivity, it is prudent to effectively manage something that can be controlled, namely soil fertility. Preventing nutrient deficiencies through proper soil fertility management will better manage the risk by producing high quality vigorous plants that are more resilient to external stressors. Assessing the soil nutrient supply prior to plantation establishment will assist in the selection of suitable afforestation sites and allowing economically and environmentally appropriate fertility amendment decisions to be made for promoting successful plantation establishment and growth. Optimizing fertilization practices by applying gained knowledge of the underlying biogeochemical cycling of soil nutrients is necessary for maximizing the economic, environmental, and societal benefits commonly associated with SRC willow production**.**

Conclusion

Establishing SRC willow plantations for providing a dedicated supply of renewable energy feedstock is advantageous, but sustaining willow production over multiple rotations is predicated on long-term soil productivity. The influence of different nutrient input, output, and transfer vectors on the plant available soil nutrient pool dynamics during the first rotation varied depending on the nutrient. Relative to the initial extractable nutrient levels at the beginning of the rotation, soil mineral

weathering inputs were negligible and atmospheric deposition was most relevant for improving soil N availability. Nutrient transfers from net mineralization of SOM accounted for the majority of N and S added to the available pools. Contributions to soil P availability were primarily from fine root turnover, while leaf litter decomposition supplied the majority of K, Ca, and Mg additions. Soil N, P, and S taken up by willow was chiefly sequestered in below-ground tissues (predominantly the fine roots), with K, Ca, and Mg largely contained in leaf litter. Leaching losses were minimal and denitrification was negligible. Despite significant (P <0.05) variety × site effects on biomass production, the lack of observed differences in soil nutrient demand among willow varieties are presumably due to offsetting relative differences in nutrient use efficiency, but further examination of their tissue nutrient data is required to confirm this. Based on the nutrient budget results from the initial four-year rotation, we found SRC willow to be relatively low nutrient-demanding, with minimal nutrient export from the plantations other than in harvested biomass. Even with very efficient nutrient cycling, observed budget deficits in soil N and P after four years suggest that sustaining harvestable yields over multiple rotations will require supplemental fertilizer amendments, albeit at application rates that are a fraction of what is typically applied to annual agronomic crops and herbaceous bioenergy species. Amendments maintaining long-term soil fertility will promote the sustainability of these purpose-grown biomass energy plantations, thus helping advance SRC willow as a viable alternative in Canada's bioenergy sector.

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Table 1 Selected site characteristics of different willow variety trial sites in Saskatchewan, Canada [adapted from 44]

Site	UTM co-ordinates	Elevation (m)	Prior crop	ACC[a]	MAP[b] (mm)	MGSP[c] (mm)	MAT[d] (^{o}C)	MGST[e] (^{o}C)	FFD[f] (#)
Prince Albert	13U 448501 5912029	493	fallow	5	450	295	1.2	14.2	85
Birch Hills	13U 467122 5872616	451	canola	1	420	277	1.3	14.3	90
Saskatoon	13U 389970 5776342	550	fallow	2	375	312	2.6	14.9	112
Estevan	13U 655043 5438201	558	fallow	3-4	430	341	3.3	15.4	124

[a] Agriculture Capability Classification (Class 1: no significant limitations; Class 2: moderate limitations; Class 3: moderately severe limitations; Class 4: severe limitations; Class 5: very severe limitations)
[b] Mean annual precipitation (snow + rainfall) [97-100]
[c] Mean growing season precipitation during the rotation; growing season length determined using 5 ^{o}C soil baseline
[d] Mean annual air temperature during the rotation
[e] Mean growing season air temperature during the rotation; growing season length determined using 5 ^{o}C soil baseline
[f] Frost-free days [97-100]

Table 2 Mean (n=24) selected soil characteristics[a] of different willow variety trial sites in Saskatchewan, Canada [adapted from 44]

Site	Soil type[b]	Texture (% sand/clay)	$pH_{1:2}$[c]	$EC_{1:2}$[d]	BD[e] ($g\ cm^{-3}$)	Organic (%)		Extractable nutrients ($kg\ ha^{-1}$)					
						C	N	N	P	K	S	Ca	Mg
Prince Albert	OBC[f]	sand to loamy-sand (91/2)	6.6c[g]	0.16c	1.5a	1.4c	0.1c	55c	148a	715c	92b	14381b	1297d
Birch Hills	OBC[h]	silt-loam to clay-loam (29/28)	7.0b	0.68a	1.0b	3.2a	0.3a	68b	16c	1297b	809a	20464a	4336b
Saskatoon	OV[i]	clay (13/70)	7.1b	0.45b	1.2b	2.3b	0.2b	99a	64b	1963a	663a	19905a	9644a
Estevan	CHR[j]	silt-loam (33/23)	8.0a	0.60ab	1.1b	2.0b	0.2b	99a	36bc	1348b	764a	19404a	3134c

[a] 0-60 cm; average values of six 10 cm segments (2 cm diameter) collected using a JMC backsaver probe (Model PN001; Clements Assoc. Inc, Newton, IA, USA), except for extractable nutrient levels that are summed values of all segments

[b] Taxonomy based on the Canadian System of Soil Classification [106]

[c] 1:2 (soil:water; on a weight basis) extraction

[d] Electrical conductivity

[e] Bulk density

[f] Orthic Black Chernozem; Meota Association; for a complete description (e.g., map unit, parent material, stoniness, drainage, etc.) see SCSR [97]

[g] Means within a column followed by the same letter are not significantly different ($P > 0.05$) using LSD

[h] Orthic Black Chernozem; Hoey-Blaine Lake Association; for a complete description see SCSR [99]

[i] Orthic Vertisol; Sutherland Association; for a complete description see SCSR [98]

[j] Cumulic Humic Regosol; Alluvium; for a complete description see SCSR [100]

Table 3 Mean (n=4) potential net N and S mineralization (0-20 cm; measured using an eight-week incubation) and historical mineral weathering of P, K, Ca, and Mg (0-60 cm; measured using the elemental depletion method) from soil collected at different willow plantations in Saskatchewan, Canada.

Site	N[a]	P	K	S	Ca	Mg
	($kg\ ha^{-1}\ year^{-1}$)					
Prince Albert	36.5b[b]	0.1	2.0	15.4b	17.6	4.9
Birch Hills	47.0a	0.1	2.2	18.7b	14.7	3.3
Saskatoon	50.4a	0.1	7.7	35.0a	3.7	2.7
Estevan	47.7a	0.1	2.4	43.8a	2.2	1.4

[a] NH_4^+-N + NO_3^--N

[b] For N and S values, means within a column followed by the same letter are not significantly different (P >0.05) using LSD. Only one sample was collected from each soil horizon within a single pedon at each site for estimating historic P, K, Ca, and Mg mineral weathering supply rates, which precluded any analysis of variance assessment

Table 4 Mean (n=16) total bulk deposition (BD), throughfall (TF), net throughfall (NTF), dry deposition (DD), and canopy exchange (CE) fluxes after three years post-coppice, measured during the growing season using open-ended polypropylene containers located outside of the plantation and under the canopy of willow variety SX64, at different locations in Saskatchewan, Canada.

	N[a]	P	K	S	Ca	Mg
	(kg ha^{-1})					
BD	32.6 (0.8)[b]	2.8 (0.2)	14.0 (1.1)	16.3 (0.7)	23.6 (1.6)	8.7 (0.8)
TF	11.6 (0.9)	7.7 (0.7)	31.9 (1.8)	26.0 (1.4)	43.1 (2.3)	13.6 (1.1)
NTF	-21.0 (1.3)	4.9 (0.6)	18.0 (0.9)	9.7 (1.2)	19.5 (1.5)	4.9 (0.8)
DD	NA[c]	1.5 (0.1)	7.3 (0.6)	10.7 (1.1)	15.6 (1.4)	5.4 (0.7)
CE	-21.0 (1.3)	3.4 (0.7)	10.6 (1.1)	-0.9 (1.6)	3.8 (1.4)	-0.5 (1.0)

[a] NH_4^+-N + NO_3^--N

[b] Overall mean (standard error) values are reported due to significant (P <0.05) site × year effect

[c] Assumed to be zero; therefore, $CE_N = NTF_N$ [12]

Table 5 Mean (n=24) biomass and nutrient content in the harvested stems (bark + wood) of several willow varieties exported offsite during the initial four-year rotation at different plantations in Saskatchewan, Canada.

Site	Biomass	N	P	K	S	Ca	Mg
	(Mg ha^{-1})	(kg ha^{-1})					
	Coppiced biomass one year after planting						
Prince Albert	1.1 (0.1)[a]	10.7 (1.1)	1.9 (0.2)	6.4 (0.9)	0.9 (0.1)	19.8 (2.2)	1.9 (0.2)
Birch Hills	0.3 (<0.1)	3.1 (0.2)	0.4 (<0.1)	1.4 (0.1)	0.3 (< 0.1)	5.5 (0.5)	0.8 (0.1)
Saskatoon	0.4 (<0.1)	3.2 (0.3)	0.4 (<0.1)	1.5 (0.2)	0.3 (<0.1)	5.2 (0.5)	1.7 (0.2)
Estevan	0.5 (<0.1)	3.8 (0.3)	0.5 (<0.1)	2.3 (0.2)	0.6 (0.1)	11.5 (0.9)	2.0 (0.2)
	Harvested biomass three years after coppicing						
Prince Albert	13.7 (1.7)	42.3 (4.8)	7.8 (0.8)	31.7 (3.6)	8.3 (1.0)	115.8 (14.6)	9.6 (1.1)
Birch Hills	19.3 (0.8)	68.6 (3.8)	10.6 (0.7)	45.9 (2.8)	11.3 (0.6)	139.2 (10.9)	17.5 (0.7)
Saskatoon	13.9 (1.1)	53.4 (5.4)	9.3 (0.9)	44.5 (3.8)	9.6 (1.2)	86.6 (7.1)	17.3 (1.3)
Estevan	26.6 (1.7)	77.4 (5.0)	7.7 (0.5)	58.0 (3.8)	11.1 (0.7)	160.8 (14.0)	21.8 (1.6)

[a] Site mean (standard error) values are reported due to significant (P <0.05) variety × site effect

Table 6 Mean (n=24) biomass and nutrient content of the stool and fine and coarse root tissues of several willow varieties after the initial four-year rotation at different plantations in Saskatchewan, Canada.

Site	Biomass	N	P	K	S	Ca	Mg
	(Mg ha^{-1})	(kg ha^{-1})					
	Stool[ab]						
Prince Albert	0.9 (0.1)[c]	3.1 (0.4)	0.5 (0.1)	1.1 (0.1)	0.8 (0.1)	1.4 (0.2)	0.6 (0.1)
Birch Hills	1.3 (0.1)	4.4 (0.2)	0.7 (<0.1)	1.6 (0.1)	1.2 (<0.1)	1.9 (0.1)	0.9 (<0.1)
Saskatoon	0.9 (0.1)	3.1 (0.2)	0.5 (<0.1)	1.1 (0.1)	0.8 (0.1)	1.4 (0.1)	0.7 (<0.1)
Estevan	1.7 (0.1)	6.0 (0.4)	1.0 (0.1)	2.2 (0.1)	1.6 (0.1)	2.7 (0.2)	1.3 (0.1)
	Fine roots[d]						
Prince Albert	10.9 (1.4)	154.2 (20.3)	36.6 (5.0)	52.8 (7.2)	34.9 (4.8)	46.0 (6.3)	35.8 (4.9)
Birch Hills	11.7 (0.7)	165.6 (9.9)	43.3 (2.7)	62.5 (3.9)	41.3 (2.6)	54.4 (3.4)	42.4 (2.6)
Saskatoon	12.1 (1.0)	170.9 (13.5)	52.8 (4.3)	76.1 (6.1)	50.3 (4.1)	66.3 (5.3)	51.6 (4.2)
Estevan	7.1 (0.8)	100.3 (11.1)	26.6 (3.3)	38.4 (4.8)	25.4 (3.1)	33.5 (4.1)	26.0 (3.2)
	Coarse roots[a]						
Prince Albert	0.6 (0.1)	4.2 (0.5)	0.8 (0.1)	1.5 (0.2)	0.8 (0.1)	1.1 (0.1)	0.8 (0.1)
Birch Hills	0.9 (<0.1)	6.0 (0.2)	1.2 (<0.1)	2.1 (0.1)	1.2 (<0.1)	1.5 (0.1)	1.2 (<0.1)
Saskatoon	0.6 (<0.1)	4.3 (0.3)	0.9 (0.1)	1.5 (0.1)	0.8 (0.1)	1.1 (0.1)	0.8 (0.1)
Estevan	1.2 (0.1)	8.3 (0.5)	1.6 (0.1)	2.9 (0.2)	1.6 (0.1)	2.1 (0.1)	1.6 (0.1)

[a] Estimated at harvest
[b] Includes both above- and below-ground component
[c] Site mean (standard error) values are reported due to significant (P <0.05) variety × site effect
[d] Estimated annually and summed

Table 7 Mean (n=4) leached nutrients during the initial four-year rotation, measured by monitoring leachate nutrient concentrations using suction lysimeters installed at 60 cm within plots of willow variety SX64, at different plantations in Saskatchewan, Canada.

Site	N[a]	P	K	S	Ca	Mg
	(kg ha^{-1})					
Prince Albert	2.6 (1.0)[b]	1.2 (0.5)	2.0 (0.2)	33.9 (4.9)	52.4 (3.7)	26.8 (3.2)
Birch Hills	1.7 (0.9)	0.1 (<0.1)	0.3 (0.1)	22.8 (1.4)	97.5 (1.5)	54.5 (3.5)
Saskatoon	8.2 (0.4)	0.1 (<0.1)	0.4 (<0.1)	22.2 (7.4)	9.0 (0.2)	22.5 (0.9)
Estevan	14.7 (4.2)	0.2 (<0.1)	1.4 (0.1)	11.2 (0.8)	23.5 (1.2)	22.6 (2.5)

[a] NH_4^+-N + NO_3^--N

[b] Site mean (standard error) values are reported due to significant (P <0.05) site × year effect

Table 8 Mean (n=24) nutrients released from fine root turnover during the initial four-year rotation for several willow varieties at different plantations in Saskatchewan, Canada[a].

	N	P	K	S	Ca	Mg
Site	(kg ha^{-1})					
Prince Albert	58.5 (7.7)[b]	12.9 (1.8)	18.6 (2.5)	12.3 (1.7)	16.2 (2.2)	12.6 (1.7)
Birch Hills	55.3 (3.5)	13.3 (0.9)	19.1 (1.2)	12.7 (0.8)	16.7 (1.1)	13.0 (0.8)
Saskatoon	52.9 (4.2)	14.8 (1.2)	21.4 (1.7)	14.1 (1.1)	18.6 (1.5)	14.5 (1.1)
Estevan	33.0 (3.7)	8.0 (1.0)	11.6 (1.4)	7.7 (0.9)	10.1 (1.2)	7.8 (1.0)

[a] Nutrient release estimated using site-specific relative proportional ratios for biomass and fine root turnover (0.96 year^{-1}) from [107] and decomposition rate (20 % year^{-1}) from [86]

[b] For each nutrient, site mean (standard error) values are reported due to significant (P <0.05) variety × site effect

Table 9 Mean (n=24) change in plant available soil nutrient pool after the initial four-year rotation for several willow varieties at different plantations in Saskatchewan, Canada.

Site	N	P	K	S	Ca	Mg
	(kg ha^{-1})[a]					
Prince Albert	-23.2a[b]	-52.6b	-75.9a	28.5c	-221.9a	-41.1a
Birch Hills	-12.4a	-39.4b	-152.9b	23.8c	-335.4a	-96.7b
Saskatoon	-12.1a	-46.0b	-100.6a	95.9b	-159.7a	-73.2ab
Estevan	-21.6a	-19.4a	-120.3a	142.9a	-365.7a	-83.9ab
	(%)[c]					
Prince Albert	-41.9b	-35.4a	-10.6b	31.0a	-1.5a	-3.2b
Birch Hills	-18.3a	-243.3b	-11.8b	2.9b	-1.6a	-2.2b
Saskatoon	-12.2a	-72.2a	-5.1a	14.5b	-0.8a	-0.8a
Estevan	-21.7a	-54.4a	-8.9b	18.7b	-1.9a	-2.7b

[a] Net nutrient balance = initial extractable soil nutrients + inputs + transfers - outputs; negative value indicates a budget deficit, while a positive value indicates a budget surplus

[b] For each unit, means within a column followed by the same letter are not significantly different (P >0.05) using LSD

[c] ((Net nutrient balance - initial extractable soil nutrient level)/initial extractable soil nutrient level) × 100; negative value indicates nutrient depletion, while a positive value indicates nutrient enrichment

Table 10 Mean (n=96) soil nutrient budget after the initial four-year rotation for several willow varieties growing at different willow plantations in Saskatchewan, Canada[a].

Budget Variable	N[b]	P	K	S	Ca	Mg
	(kg ha^{-1})					
Initial extractable soil nutrients[c]	79.6 (2.1)	66.1 (5.7)	1322.1 (49.1)	579.3 (32.3)	18524.0 (273.3)	4573.6 (342.7)
Inputs						
Soil mineral weathering[c]	0.0	0.2 (<0.1)	14.4 (1.1)	0.0	39.4 (3.0)	12.4 (0.6)
Atmospheric deposition	22.6 (0.5)	6.5 (0.1)	25.8 (0.1)	31.4 (0.1)	47.6 (0.6)	17.4 (0.3)
Outputs						
Coppiced stems	-5.4 (0.5)	-0.8 (0.1)	-3.0 (0.4)	-0.6 (<0.1)	-10.9 (1.0)	-1.7 (0.1)
Harvested stems	-60.2 (2.8)	-8.9 (0.4)	-44.7 (2.0)	-10.1 (0.5)	-125.4 (6.6)	-16.4 (0.8)
Leaf litter	-82.7 (3.7)	-15.5 (1.7)	-115.5 (8.0)	-25.7 (1.5)	-264.9 (16.8)	-42.6 (2.4)
Stool and roots[d]	-158.6 (7.6)	-41.8 (2.2)	-61.2 (3.1)	-40.4 (2.1)	-53.6 (2.7)	-41.1 (2.1)
Leaching[e]	-6.6 (0.6)	-0.4 (0.1)	-1.1 (0.1)	-20.2 (0.6)	-44.7 (3.8)	-32.2 (1.5)
Transfers						
Soil net mineralization[f]	181.2 (2.4)	0.0	0.0	110.6 (5.1)	0.0	0.0
Canopy exchange[g]	0.0	3.2 (0.1)	10.8 (0.1)	0.0	3.4 (0.4)	0.0
Leaf litter decomposition	21.1 (1.5)	3.9 (0.4)	47.5 (5.2)	10.5 (0.7)	110.9 (9.4)	18.4 (1.0)
Fine root turnover	50.4 (2.7)	12.3 (0.7)	17.8 (1.0)	11.8 (0.6)	15.5 (0.8)	12.1 (0.7)
Net soil nutrient balance[h]	62.3 (7.0)	26.4 (5.2)	1209.3 (48.6)	639.5 (35.0)	18241.7 (270.7)	4499.9 (342.0)
% Change in soil nutrients[i]	-23.7 (10.2)	-104.6 (10.3)	-9.2 (0.6)	16.6 (1.7)	-1.5 (0.1)	-2.2 (0.1)

[a] Overall mean (standard error) values are reported due to significant (P <0.05) variety × site effect

[b] NH_4^+-N + NO_3^--N whenever applicable

[c] 0-60 cm

[d] Stool and coarse root biomass estimated at harvest and fine root biomass estimated annually and summed

[e] Leachate collected at 60 cm depth and assumed to be lost to willow uptake

[f] 0-20 cm

[g] Zero values indicate foliar consumption of atmospheric nutrients (i.e., negative canopy exchange values; Table 4). These nutrients did not originate from the soil, but are a component of the biomass output values; therefore, the net soil nutrient balance value for N, S, and Mg was credited accordingly

[h] Initial extractable soil nutrients + inputs + outputs + transfers. Reported value is mean of all site/plot data; not calculated from table data

[i] ((Net nutrient balance - initial extractable soil nutrient level)/initial extractable soil nutrient level) × 100. Reported value is mean of all site/plot data; not calculated from table data

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